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A COMPLETE E, P, V, T, S THERMODYNAMIC DESCRIPTION OF METALS BASED ON THE P, u MIRROR-IMAGE CONCEPT

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A Complete E,P,V,T,S Thermodynamic Description of Metals Based on the P,u Mirror-Image Concept

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ABSTRACT: The well-known practice of using the mirror-image, in the P,u plane, of the shock Hugoniot curve about a vertical line through the shocked state P_H, u_H is shown to give a complete thermodynamic description of metals when the U(shock velocity) vs. u_H relationship and $\alpha \equiv V^{-1}(\partial V/\partial T)_{P\approx 0}$ are known. Use of the experimental relationship $U = c_o + au_H$ (a and c_o constants) and α = constant, leads to a thermodynamic description which results in the metal appearing less compressible than if described by the Mie-Grüneisen equation of state. Furthermore, the existance of an anomalous behavior of c_p in the low pressure neighborhood (<10 to <50 kbar depending on the metal) of the initial state rules out the simultaneous existance of a Hugoniot satisfying the linear U vs. u_H relationship, of isentropes satisfying the mirror-image assumption, and of a constant value of α in this neighborhood. Thermodynamic functions for 16 metals are calculated up to 2 megabars and compared with the results obtained from the Mie-Grüneisen equation of state.

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This work was carried out under FR-59, Transition from Deflagration to Detonation. An important problem in this field is the lack of an adequate equation of state for solid materials. The work of this report is an original contribution in this area.

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I. INTRODUCTION

A problem which is encountered quite often in experimental shock dynamics is the determination of the pressure and particle velocity behind the transmitted shock in a specimen after the initial shock, having traveled through a metal standard, has interacted with the interface between the specimen and the standard. An important application of this problem is the determination of the experimental shock Hugoniot of the specimen as a first step toward finding its equation of state. Consider a shock traveling to the right through a metal standard whose initial conditions (given by the subscript o) are $u_o = 0$, E_o, V_o, $P_o \approx 0$, where u,E,V,P are respectively, the particle velocity, specific internal energy, specific volume, and pressure. A pressure P_o of at most a few bars is considered negligible in present considerations since the pressures of interest are in the kilobar to megabar range. When this shock interacts with the interface a shock is transmitted into the specimen and a wave traveling to the left is reflected into the standard. The loci of P,u points that can be reached by the initial shock and the reflected wave in the standard are shown in Fig. 1. For pressures greater and particle velocities smaller than that corresponding

to the initial shock, the reflected wave is a reflected shock. For smaller pressures and greater particle velocities, the reflected wave is a reflected rarefaction wave. The shock equation

$$P_H = \rho_o U u_H \qquad (1)$$

relates the shock pressure P_H, shock velocity U, shock particle velocity u_H, and initial density $\rho_o (=1/V_o)$. From now on the subscript H will always refer to values on the shock Hugoniot. Hence the measurement of ρ_o and U (of the transmitted shock) in the specimen implies that P_H and u_H (in the specimen) lie on the straight line of known slope $\rho_o U$ as given by Eq. (1). If this is depicted by the dashed line in Fig. 1, then the intersection with the rarefaction wave in the standard is the desired pressure P_1 and particle velocity u_1 behind the transmitted shock in the specimen (since P and u are continuous at the interface).

It will always be assumed that the effects of material rigidity can be neglected since the shock pressures are far greater than the yield point of the metals involved. Hence the metal can be treated as a fluid with an ordinary equation of state.

The calculation of the rarefaction waves (isentropes) entails a knowledge of the E,P,V equation of state.

Walsh and Christian[1] computed the temperatures along the Hugoniot and the isentropes for Al, Cu and Zn from the Hugoniot curves combined with the assumption that the specific heat at constant volume c_v and $(\partial P/\partial T)_V$ are constants. Walsh and Rice[2] noted that at least for Al the changes in the P,u isentropes are insensitive to changes in the value of $(\partial P/\partial E)_V$. Walsh, et al,[3] employed the Mie-Grüneisen equation of state for which the volume dependence of the Grüneisen ratio was determined using the Dugdale-MacDonald relation. These considerations allowed them to compute the isentropes in the neighborhood of the experimental Hugoniot curve. Additional zero-pressure data then permitted the calculation of the remaining thermodynamic data of interest, and numerical results were tabulated for 27 metals. McQueen and Marsh[4] applied the previous theory to more extensive experimental data in the one-to-two megabar region for 16 metals. Their experimental shock measurements actually covered 19 metallic elements. Al'tshuler, et al,[5,6] have reported investigations of iron to shock pressures of about 5 megabars, and 3 to 5 megabars for Ag,Au,Bi,Cd,Cu,Pb,Sn, and Zn. The Mie-Grüneisen equation of state, in which the Grüneisen ratio was considered to be a constant, was used to describe iron. Further work[7] on Al,Cu, and Pb took into account the

electronic components of the energy and pressure.

Consider for a moment that the specimen mentioned in the problem above is replaced by a vacuum (approximating air at several bars pressure). When the plane shock in the metal which connects the state $P_o \approx 0$, $u_o = 0$ and P_H, u_H arrives at a free surface, the pressure in the shock is reduced to zero by a rarefaction wave from the surface. Let u_{fs} be the free surface particle velocity. It was first postulated by Goranson[8] about 1945 that for most metals

$$2\, u_H \approx u_{fs}. \qquad (2)$$

Thus experimental values of U and u_{fs} determine the Hugoniot. In fact this approximation is the first guess in a rapidly convergent iterative procedure for bounding[1] and determining[2,3,4] the Hugoniot when additional thermodynamic information is given. Tabulated results[1,3,4] show that this approximation is fairly accurate for many metals.

For metals a further assumption (which includes Eq. (2) as a special case) is frequently made. The isentropic expansion from P_H, u_H to $0, 2u_H$ is approximated by taking the mirror-image of the Hugoniot curve about a vertical line through P_H, u_H in the P,u plane (see, for example, Refs. 9 and 10). This makes it particularly simple to calculate P_1, u_1. One need have only the Hugoniot

P,u curve for the metal, reflect it about the appropriate point corresponding to the measured shock velocity in the metal, and find the intersection of this reflected curve with the straight line given by Eq. (1) (dashed line of Fig. 1). Under this assumption the curve of an isentropic compression from the point $u_o = 0, E_o, P_o \approx 0, V_o$ coincides with the Hugoniot in the P,u plane, but intersects it only once in the P,V plane. Hence the Hugoniot is not an isentrope as one might be apt to think at first glance.

Since the mirror-image assumption is often used it is worth examining its consequences, and in the remainder of this paper it will be shown that this assumption and the experimental U, u_H relation are enough to determine a unique E,P,V equation of state in the metal. Furthermore an experimental thermal coefficient of volume expansion along the isobar $P_o \approx 0$ determines the temperature T, entropy S, and other thermodynamic properties as functions of any two thermodynamic variables, e.g., P and V. In Section II the Hugoniot relations valid for many metals are given. An exact though complicated E,P,V equation of state which is a direct consequence of the mirror-image assumption is derived in Section III. Section IV contains the derivation of the temperature, entropy, and specific heat at constant

pressure. The anomalous behavior of the latter in the low pressure region where the Hugoniot is not well defined is discussed. Finally, in Section V, tabulated results for various thermodynamic quantities for 16 metals based on the mirror-image approximation are compared with results obtained by McQueen and Marsh[4] who utilized the more sophisticated Mie-Grüneisen equation of state.

II. THE HUGONIOT CURVE

Many investigators have found that for many metals the shock velocity is linear in the shock particle velocity, i.e.,

$$U = c_o + a\, u_H. \tag{3}$$

Theoretically, c_o should be the adiabatic sound speed at the initial state $E_o, P_o, V_o, u_H = 0$. Least-square straight-line fits of the experimental U, u_H data[4] give as the intercepts c_o values that are quite close to the isentropic sound speeds at P_o, V_o,

$$c_o(B) = V_o \left(\frac{-\partial P}{\partial V}\right)_S^{\frac{1}{2}} = \lim_{u_H \to o} U = \lim_{\substack{P_H \to P_o \\ V_H \to V_c}} V_o \left(\frac{P_H - P_o}{V_o - V_H}\right)^{\frac{1}{2}}, \tag{4}$$

which were computed[4] from Bridgeman's data by applying a small correction for the difference between isothermal and isentropic first derivatives.

Elimination of U between Eqs. (1) and (3) yields

$$P_H = \rho_o u_H (a u_H + c_o). \tag{5}$$

From the other two relations valid on the Hugoniot,

$$u_H^2 = P_H (V_o - V_H), \tag{6}$$

$$E_H - E_o = \tfrac{1}{2} P_H (V_o - V_H), \tag{7}$$

V_H and E_H can be written as functions of u_H:

$$V_o - V_H = V_o u_H / (a u_H + c_o), \tag{8}$$

$$E_H - E_o = \tfrac{1}{2} u_H^2. \tag{9}$$

From Eqs. (6) and (8), the equation of the Hugoniot in the P,V plane is

$$P_H = c_o^2 (V_o - V_H) / \left[(a-1)V_o - aV_H\right]^2 ; \tag{10}$$

the slope of the Hugoniot is

$$dP_H / dV_H = -\rho_o^2 (2au_H + c_o)(au_H + c_o)^2 / c_o < 0. \tag{11}$$

<u>If</u> Eq. (3) holds for all shock strengths, then letting $P_H \to \infty$ in Eq. (10) leads to

$$\rho_{max}/\rho_o = V_o/V_{min} = a/(a-1), \quad a>1, \tag{12}$$

where $\rho_{max} (= 1/V_{min})$ is the maximum density that can be obtained with a single shock starting at ρ_o.

III. THE E,P,V EQUATION OF STATE

If $P_H = h(u_H)$ refers to the Hugoniot pressure-particle velocity curve, and $P(u;u_H)$ refers to the pressure-particle velocity curve for an isentropic expansion from a point P_H, u_H, then the assumption that the expansion from the shocked state P_H, u_H is the mirror

image of the Hugoniot about a vertical line through P_H, u_H is expressed by

$$P(u;u_H) = h(2u_H - u), \tag{13}$$

where u_H is now a continuous parameter but constant for each isentrope. Actually u_H is a single-valued function of the entropy; the explicit relationship is derived in Section IV. By Eq. (5),

$$P(u;u_H) = \rho_o(2u_H - u)\left[a(2u_H - u) + c_o\right]. \tag{14}$$

The solution for u as a function of P is

$$2u_H + \frac{c_o}{2a} - u = \left[\frac{P}{\rho_o a} + \left(\frac{c_o}{2a}\right)^2\right]^{\frac{1}{2}}, \tag{15}$$

where the positive root is taken for $u \leq 2u_H$. Since

$$dP(u;u_H)/du = \rho_o(2au - 4\,au_H - c_o), \tag{16}$$

the equation,

$$(du)^2 + dPdV = 0, \tag{17}$$

valid on an isentrope, can now be integrated between the points u_H, V_H and u,V to give

$$2\rho_o a(V_H - V) = \ln\left[1 + 2a(u_H - u)/(2au_H + c_o)\right]. \tag{18}$$

Elimination of u between Eqs. (15) and (18) leads to the isentropic equation

$$4aP(V;u_H) = \left(4aP_H + \rho_o c_o^2\right)e^{-4a\rho_o(V-V_H)} - \rho_o c_o^2. \tag{19}$$

Define a new parameter

$$z = au_H/c_o = (U - c_o)/c_o. \tag{20}$$

With the use of Eqs. (5), (8), and (20), Eq. (19) can be rewritten as

$$\Psi(P,V) \equiv \left(1+4aV_oP/c_o^2\right)e^{4a\rho_o(V-V_o)} =$$
$$= (2z+1)^2\, e^{-4z/(z+1)} \equiv w(z), \tag{21}$$

where $\Psi(P,V)$ and $w(z)$ are defined as, respectively, the left-and right-hand sides of Eq. (21). Using Eq. (19), the adiabatic sound speed c can be obtained from

$$\rho^2c^2 \equiv -(\partial P/\partial V)_S = 4a\rho_oP + \rho_o^2c_o^2\,, \tag{22}$$

which defines the slopes of the P,V isentropes[11]

The energy along the isentrope is found from

$$E(V;u_H) - E_H = -\int_{V_H}^{V} P(V';u_H)\, dV' \tag{23}$$

to be,

$$4a\left[E(V;u_H) - E_H\right] - \rho_oc_o^2(V-V_H) - V_o\left[P(V;u_H) - P_H\right] = 0 \tag{24}$$

where Eq. (19) has been used. In more convenient form, Eq. (24) can be written as

$$\left(\frac{c_o}{2a}\right)^2 \Phi(E,P,V) \equiv E-E_o-\frac{\rho_oc_o^2}{4a}(V-V_o) - \frac{PV_o}{4a} =$$
$$= E_H-E_o-\frac{\rho_oc_o^2}{4a}(V_H-V_o) - \frac{P_HV_o}{4a}\,. \tag{25}$$

Since the right-hand side of Eq. (25) is just a function of u_H,

$$\Phi(E,P,V) = z^3/(z+1) \geq 0. \tag{26}$$

If z can be eliminated between Eqs. (21) and (26), the resulting equation would define the desired E,P,V equation of state. This may be accomplished by solving Eq. (26),

$$z^3 - \Phi z - \Phi = 0,$$

for the single positive root z (Φ) and then substituting this into Eq. (21). In order to find the root the following two cases must be considered:

(i) If $4\Phi \leq 27$, then the positive root is given by

$$z = \left(\tfrac{1}{2}\Phi\right)^{\frac{1}{3}} \left\{\left[1+\left(1-\frac{4}{27}\Phi\right)^{\frac{1}{2}}\right]^{\frac{1}{3}}+\left[1-\left(1-\frac{4}{27}\Phi\right)^{\frac{1}{2}}\right]^{\frac{1}{3}}\right\}. \tag{27}$$

(ii) If $4\Phi \geq 27$, then the positive root is given by

$$z = 2\left(\Phi/3\right)^{\frac{1}{2}} \cos\left(\tfrac{1}{3}\theta\right), \tag{28}$$

where

$$0 < \cos\theta = \tfrac{1}{2}\left(27/\Phi\right)^{\frac{1}{2}} \leq 1, \quad 0 \leq \theta < \frac{\pi}{2}. \tag{29}$$

Hence the isentrope characterized by $z = 3$ (i.e., the isentrope that intersects the Hugoniot when $U = 4\ c_o$) divides the P,V plane into two regions. Eq. (27) holds above this isentrope, Eq. (28) below. Therefore Eqs. (21), (27), (28), and (29) define the E,P,V equation of state, i.e.,

$$\Psi(P,V) = w\left(z\left[\Phi(E,P,V)\right]\right). \tag{30}$$

IV. CALCULATION OF T, S, AND c_p

The derivation of the thermal equation of state which gives the temperature as a function of pressure and volume proceeds in the following manner. Along an isentrope,

$$TdS = c_v dT + T(\partial P/\partial T)_V \, dV = 0, \tag{31}$$

where c_v is the specific heat at constant volume. Since

$$c_v(\partial P/\partial E)_V = (\partial P/\partial T)_V, \tag{32}$$

the integral of Eq. (31) is obtained from

$$\int_{T(0,V)}^{T(P;z)} \frac{dT'}{T'} = -\int_0^P \left(\frac{\partial P'}{\partial E}\right)_V \left(\frac{\partial V}{\partial P'}\right)_S dP' \, . \tag{33}$$

The lower limit of the first integral, $T(0,V)$, is found from the experimental coefficient of volume expansion along the isobar $P \approx 0$. Let $T(0,V) = T_o f(V/V_o)$, where T_o is the initial temperature corresponding to E_o, V_o, P_o, and f is an arbitrary function of V/V_o. From Eq. (21),

$$g(z) \equiv \frac{V}{V_o} = 1 + \frac{1}{2a} \ln (2z+1) - \frac{z}{a(z+1)} \text{ on } P \approx 0. \tag{34}$$

Define $F(z) \equiv T(0,V)/T_o = f[g(z)]$. Differentiation of Eq. (30) with respect to P gives

$$(\partial E/\partial P)_V = \left[(d\Phi/dz)(dz/dw)\partial\Psi/\partial P - \partial\Phi/\partial P\right]\partial E/\partial\Phi, \tag{35}$$

and evaluation of the derivatives leads to

$$\left(\frac{\partial E}{\partial P}\right)_V = \frac{V_o}{4a}\left[1 + \frac{(2z+3)(2z+1)}{1+4aPV_o/c_o^2}\right] . \tag{36}$$

Substitution of Eqs. (22) and (36) into Eq. (33) gives the result,

$$T(P;z)/T_o = F(z)\left\{1+aP/\left[\rho_o c_o^2 (z+1)^2\right]\right\} , \qquad (37)$$

on the isentrope characterized by the value of z. Eqs. (21) and (37) determine the P,V,T equation of state through the parameter z.

By Eqs. (25) and (34),

$$4a^2[E(z)-E_o]/c_o^2 = z(z-1) + \tfrac{1}{2}\ln(2z+1) \text{ on } P\approx 0. \qquad (38)$$

On the isobar $P\approx 0$, the entropy S can be calculated from

$$T_o(S-S_o) = \int_o^z \frac{1}{F(Z)} \frac{dE(Z)}{dZ} dZ. \qquad (39)$$

Hence the evaluation of Eq. (39) relates S to z, namely,

$$\frac{a^2 T_o}{c_o^2}[S(z)-S_o] = \int_o^z \frac{Z^2 dZ}{(2Z+1)F(Z)} . \qquad (40)$$

The positiveness of the integrand implies that S is a single-valued function of z. Of course this relation holds not only on $P\approx 0$ but on all paths connecting the isentropes S_o and S.

A complete E,P,V,T,S thermodynamic description of the metal has now been obtained. For example, given the point P_1,V_1, the parameter z_1 can be obtained from Eq. (21) by simple numerical methods. Then E_1,T_1, and S_1 are computed respectively from Eqs. (25), (26), (37), and (40); in

general S_1 necessitates a numerical integration. The equations of state derived above hold in the region of the P,V plane that lies to the right of the isentrope through the point P_o, V_o, E_o in the direction of increasing entropy. If a Hugoniot of only finite length is considered (because the experimental data is limited), then the region of definition of the above equations of state is limited to the region bounded by the isentropes that pass through the lower and upper points of the Hugoniot (see Fig. 2).

The specific heat at constant pressure,

$$c_p \equiv T(\partial S/\partial T)_P = T(dS/dz)(\partial z/\partial T)_P, \tag{41}$$

found by differentiation of Eqs. (37) and (40), is

$$\frac{a^2 T_o}{c_o^2} c_p(P,z) = \frac{z^2(z+1)\left[aP+\rho_o c_o^2(z+1)^2\right]}{(2z+1)\left\{(z+1)\left[aP+\rho_o c_o^2(z+1)^2\right]dF/dz - 2aPF(z)\right\}} \tag{42}$$

In particular on the isobar $P\approx 0$,

$$(a/c_o)^2 T_o c_p(0,z) = z^2 \Big/ \left[(2z+1)dF/dz\right]. \tag{43}$$

Thus far the temperature variation with volume for $P\approx 0$ has been given as an arbitrary function of the entropy, $F[z(S)]$. In order to find the explicit form the thermal coefficient of volume expansion α will be considered as constant on $P\approx 0$, i.e.,

$$V^{-1}(\partial V/\partial T)_{P\approx 0} \equiv \alpha = \text{constant} \tag{44}$$

where the constant is experimentally determined.

Integration of Eq. (44) and use of Eq. (34) leads to the result,

$$F(z) = 1 + \frac{1}{\alpha T_o} \ln\left[1 + \frac{1}{2a} \ln(2z+1) - \frac{z}{a(z+1)}\right], \qquad (45)$$

from which it follows that

$$\frac{a}{\alpha c_o^2} c_p(P,z) = \frac{(z+1)^2 g(z)}{1-2a^2\alpha T_o(z+1)(2z+1)F(z)P/\left[az^2P+\rho_o c_o^2 z^2(z+1)^2\right]}, \qquad (46)$$

$$c_p(0,z) = \alpha c_o^2 (z+1)^2 g(z)/a. \qquad (47)$$

Since, with the use of Eq. (21),

$$\alpha T_o F(z) = \alpha T_o - \ln(4a) + \ln[4a + \ln \Psi(P,V)], \qquad (48)$$

Eq. (37) can be solved for z with the aid of Eq. (48), yielding

$$z = \left(\frac{aP}{\rho_o c_o^2}\right)^{\frac{1}{2}} \left[\frac{\alpha T}{\alpha T_o - \ln(4a) + \ln[4a - \ln \Psi(P,V)]}\right]^{-\frac{1}{2}} - 1 . \qquad (49)$$

Substitution of Eq. (49) into Eq. (21) leads to an exact though quite complicated P,V,T equation of state.

Close examination of Eq. (46) shows that c_p exhibits certain very undesirable behavior. First $c_p(P,0) = 0$ for $P>0$, i.e., c_p vanishes on the isentrope passing through the point E_o, P_o, V_o. Furthermore, the denominator of Eq. (46) vanishes on the curve C (dashed curve in Fig. 2) defined by

$$P(z) = \rho_o c_o^2 z^2 (z+1)^2 / [2a^2 \alpha T_o (z+1)(2z+1)F(z)g(z) - az^2], \qquad (50)$$

implying that $c_p \to \infty$ or $-\infty$ in the neighborhood of C depending on the direction of approach. This curve intersects the Hugoniot at the values of z given by the roots of

$$z = 2a\alpha T_o(z+1)F(z)g(z). \tag{51}$$

The lower point of intersection z_ℓ can be approximated by

$$z_\ell \approx 2a\alpha T_o \ll 1; \tag{52}$$

the upper point of intersection occurs at pressures which are much greater than the upper limit of the experimental shock pressures and therefore need not be considered. The shock pressure at which $c_p \to \pm \infty$ is

$$P_H(z_\ell) \approx 2\rho_o c_o^2 \alpha T_o, \tag{53}$$

which for the metals considered is in the range of 10 to 50 kilobars (see Table I). Certainly the equations of state derived above are not valid in the neighborhood of C (i.e., where $c_p \to \pm \infty$) or in the region (see Fig. 2) to the left of C (i.e., where $c_p \leq 0$). Numerical computations for the 16 metals show that for pressures up to at least 5 megabars (and in most cases much higher) the pressure increases monotonically with increasing z and decreasing V on the curve C. Furthermore for $P<P_H(z_\ell)$ and $P>P_H(z_\ell)$, C lies respectively to the right and to the left of the Hugoniot (as shown in Fig. 2). Along the Hugoniot, the specific heat $c_{p,H}$ rapidly decreases from ∞ at $P_H(z_\ell)$ to a minimum (at which the pressure is at most 0.2 megabars as can be seen in Table II) and then slowly increases.

The anomalous behavior of c_p leads to the conclusion that it is impossible to postulate the simultaneous existance of (i) a Hugoniot satisfying Eq. (3) and (ii) of isentropes satisfying the mirror-image assumption, both in the low pressure neighborhood of P_o, V_o, E_o, and (iii) of a constant thermal coefficient of volume expansion along $P \approx 0$. Walsh, et al, using the Mie-Grüneisen equation prescribed in addition to (i) and (iii), the experimental values for c_p along $P \approx 0$. Since the Gruneisen ratio was taken as a function of V only it was easy to show that c_p was a function of S only. Therefore c_p was well-behaved in their calculations. The conclusion is that the mirror-image assumption in the neighborhood of the low pressure Hugoniot given by Eq. (3) leads to the anomalous behavior of c_p. However it is just in this region that it is not possible to determine experimentally a unique Hugoniot. For sufficiently low pressures the effects of material rigidity (which have been neglected in the above analysis) give rise to elastic-plastic wave structures. Here an arbitrary assumed shock wave will break up into two compression waves, an elastic wave which precedes a plastic wave. This "two-wave" structure indicates that at some point on the Hugoniot locus of P,V states, there is a violation of the Bethe-Weyl necessary condition $(\partial^2 P/\partial V^2)_S > 0$, for the existance of a stable shock in a single phase fluid.

A. Special Results on the Hugoniot

It is readily seen that on the Hugoniot curve,

$$P_H = \rho_o c_o^2 \, z(z+1)/a, \tag{54}$$

$$V_H/V_o = 1 - z/[a(z+1)], \tag{55}$$

$$E_H = E_o + \tfrac{1}{2} c_o^2 z^2/a^2, \tag{56}$$

$$T_H = T_o \, F(z)[1+z/(z+1)], \tag{57}$$

$$U = c_o(z+1), \tag{58}$$

$$c_{p,H} = \frac{\alpha c_o^2 z(z+1)^3 g(z)/a}{z-2a\alpha T_o(z+1)g(z)F(z)}, \tag{59}$$

$$c_H = c_o(2z+1)(1-z/[a(z+1)]), \tag{60}$$

V. RESULTS FOR 16 METALS

In Sections III and IV it was shown that under the mirror-image assumption a complete thermodynamic description of a metal depended only on the experimental values of c_o and a, and the coefficient of volume expansion along the isobar, $P \approx 0$. These data are listed in Table I. The U, u_H curves of the 16 metals of Table I were obtained[4] by applying the method described at the very beginning of Section I. Different known shock velocities in a brass standard, whose equation of state is of the Mie-Grüneisen form, give rise to different measured shock velocities in the specimen (any one of the 16 metals), and hence to a U, u_H locus for the specimen. Columns 7 and 8 of Table I compare the specific heat $c_p = \alpha c_o^2/a$ at P_o, V_o (see Eq. (47)) obtained from the mirror-image assumption with the handbook values $c_p^{(3)}$ listed by Walsh, et al.[3]

A summary of calculations and results based on this assumption is given in Table II and these results may be compared with those obtained by McQueen and Marsh using the Mie-Grüneisen equation of state (see Table IV of Ref. 4). It is found that the mirror-image assumption always leads to smaller values of the free-surface volume (i.e., at $P \approx 0$) resulting from expansion from the shocked state. For example, for copper, corresponding to the entries of column

10 of Table II, the Mie-Grüneisen equation gives for the free-surface volumes, V/V_o = 1.000, 1.000, 1.001, 1.003, 1.006, 1.010, 1.015, 1.019, 1.025, 1.031, 1.037, 1.044, 1.051, 1.058, 1.066, and 1.079. Furthermore, along the isentropes tabulated, V/V_o is always smaller for identical pressures except in the case of thallium (see columns 14 and 15 of Table II); and for identical P the differences between the compressions, $[V(P,z)-V_H(z)]/V_H(z)$, calculated with each equation of state (starting from the same $P_H(z)$, $V_H(z)$), are smallest at high pressures (particularly for Mo, Ni, Ti, V, and W) and greatest at low pressures. As a consequence the temperatures, both along the Hugoniot and along the isentropes, are also lower (and for some metals very much lower) with the mirror-image assumption[12]. For example, for copper, corresponding to the entries of column 4 of Table II, the Mie-Gruneisen equation gives for the Hugoniot temperatures (in ^oK), T_H = 293, 334, 391, 472, 582, 719, 881, 1068, 1277, 1506, 1755, 2020, 2301, 2596, 2902, and 3042.

The results of these computations demonstrate that the thermodynamic description obtained by the mirror-image assumption causes the metal to appear less compressible than when the thermodynamic description is obtained from the Mie-Grüneisen equation of state.

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(12) While in this work the coefficient of volume expansion α is taken as a constant for each metal, it was not in Ref. 4. This has some effect on the computed temperatures but accounts for only a small part of the differences between the temperatures obtained from the mirror-image and Mie-Grüneisen equations of state.

Table I. Input data and comparison with zero-pressure data. The values of ρ_o, c_o, a, and $c_o^{(B)}$ are taken from Reference 4 (see their Table III); and the thermal coefficient of volume expansion α and the specific heat $c_p^{(3)}$ are handbook values from Reference 3 (see their Table I), except as indicated. The quantity $c_p(0,0) = \alpha c_o^2/a$ appearing in column 8 is the theoretical specific heat obtained by letting $z \to 0$ in Eq. (47). The quantities $c_o^{(B)}$, $c_p^{(3)}$, and $c_p(0,0)$ are values at the initial state $P_o \approx 0$, V_o. $P_H(z_\ell)$, the calculated shock pressure at which $c_p \to \pm \infty$, is computed from Eqs. (51) and (54).

Material	ρ_o g/cm^3	$\alpha \times 10^6$ /°K	a	c_o cm/μsec	$c_o^{(B)}$ cm/μsec	$c_p^{(3)}$ (cal/g)/°K	$c_p(0,0)$ (cal/g)/°K	$P_H(z_\ell)$ kilobars
Ag	10.49	56.7	1.586	0.3243	0.319	0.056	0.090	40.9
Au	19.24	42.6	1.560	0.3075	0.305	0.031	0.043	49.2
Cd	8.64	89.4	1.671	0.2443	0.241	0.055	0.076	32.6
Co	8.82	36.9	1.330	0.4748	0.463	0.099	0.149	45.6
Cr	7.10	18.6	1.465	0.5217	0.515	0.111[a]	0.083	21.7
Cu	8.90	49.5	1.497	0.3958	0.398	0.092	0.124	44.2
Mo	10.20	15	1.238	0.5157	0.519	0.061	0.077	24.4
Ni	8.86	39	1.445	0.4646	0.463	0.105	0.139	46.8
Pb	11.34	85.1	1.517	0.2028	0.202	0.030,	0.055	27.3
Sn	7.28	60	1.476	0.2640	0.276	0.054	0.068	19.9
Th	11.68	33.3	1.278	0.2132	0.205	0.030	0.028	10.9
Ti	4.51	25.5	1.089	0.4779	0.484	0.126	0.128	15.9
Tl	11.84	114	1.515	0.1859	0.183	0.031	0.062	34.1
V	6.1	23.4[b]	1.210	0.5108	0.518	0.115[a]	0.121	22.6
W	19.17	17.4[b]	1.268	0.4005	0.405	0.032[a]	0.053	32.2
Zn	7.14	100	1.559	0.3050	0.303	0.092	0.143	47.5

[a] Smithsonian Physical Tables, prepared by W. E. Forsythe (Smithsonian Institution, Washington, D.C., Ninth Revised Edition, 1954), pp. 155, 157

[b] Reference a, p. 146

TABLE II. Summary of calculations and results. The columns headed "shock wave parameters" refer to hydrodynamic and thermodynamic quantities associated with the various shock pressures listed in column 2. The columns headed "isentropic release-wave parameters at P≈0" refer to the hydrodynamic and thermodynamic quantities of the material relieved isentropically to zero pressure from P_H. The last three columns are the relative volume[a] computed from the Mie-Gruneisen equation of state ($V^{(G)}/V_o$), and the relative volume and temperature from the mirror-image assumption, for the isentrope that intersects the Hugoniot at the pressure corresponding to the smallest relative volume in column 14 (and 15); the pressure P in the second column now refers to the corresponding pressure for these parameters. The data in columns 2, 3, 5, and 6 are identical with that in columns 2, 3, 7, and 8 of Table IV of Ref. 4 since they are all derived from Eq. (3) which is a least-squares fit of the experimental U,u data[4]. Columns 4, 7, 10, and 11 are analogous to, respectively, columns 5, 6, 10, and 11 of Table IV of Ref. 4. The dimensions are: P in megabars, T, T_H in °K, c, c_H, u_H, U in cm/μsec, and c_p, $c_{p,H}$ in (cal/g)/°K.

Material	Shock wave parameters								Isentropic release-wave parameters at P 0				Isentrope parameters		
	P	V_H/V_o	T_H	c_H	u_H	U	$c_{p,H}$	z	V/V_o	T	c	c_p	$V^{(G)}/V_o$	V/V_o	T
Ag	0.	1.000	293	0.324	0.	0.324	-0.	0.	1.000	293	0.324	0.090	1.171	1.036	921
	0.1	0.929	332	0.366	0.026	0.378	0.245	0.1275	1.000	298	0.324	0.114	1.153	0.965	951
	0.2	0.881	378	0.400	0.048	0.419	0.242	0.2332	1.001	318	0.325	0.137	0.960	0.916	981
	0.3	0.845	435	0.430	0.067	0.452	0.282	0.3254	1.003	349	0.325	0.158	0.901	0.878	1011
	0.4	0.817	500	0.457	0.083	0.481	0.333	0.4083	1.005	387	0.326	0.179	0.863	0.848	1041
	0.5	0.794	570	0.481	0.099	0.507	0.389	0.4843	1.008	430	0.327	0.199	0.834	0.823	1071
	0.6	0.775	643	0.504	0.113	0.530	0.450	0.5548	1.010	474	0.328	0.219	0.811	0.801	1101
	0.7	0.758	719	0.526	0.127	0.551	0.515	0.6209	1.013	520	0.329	0.239	0.790	0.782	1131
	0.8	0.744	796	0.546	0.140	0.571	0.584	0.6832	1.016	566	0.329	0.258	0.772	0.765	1162
	0.9	0.731	873	0.565	0.152	0.589	0.657	0.7425	1.018	612	0.330	0.278	0.755	0.749	1192
	1.0	0.720	951	0.583	0.163	0.607	0.734	0.7991	1.021	658	0.331	0.297	0.740	0.735	1222
	1.1	0.710	1028	0.601	0.174	0.623	0.815	0.8533	1.024	704	0.332	0.316	0.725	0.722	1252
	1.2	0.700	1105	0.618	0.185	0.638	0.899	0.9054	1.026	749	0.333	0.335	0.713	0.710	1282
	1.3	0.692	1180	0.634	0.195	0.653	0.988	0.9556	1.029	793	0.334	0.353	0.701	0.699	1312
	1.4	0.684	1255	0.650	0.205	0.667	1.081	1.0042	1.031	836	0.334	0.372	0.690	0.689	1342
	1.5	0.677	1329	0.665	0.215	0.681	1.177	1.0513	1.034	879	0.335	0.391	0.680	0.679	1372
	1.6	0.670	1402	0.680	0.224	0.694	1.278	1.0969	1.036	921	0.336	0.409	0.670	0.670	1402
Au	0.	1.000	293	0.307	0.	0.307	-0.	0.	1.000	293	0.307	0.062	1.113	1.026	905
	0.1	0.953	316	0.332	0.016	0.340	0.166	0.0794	1.000	295	0.308	0.072	1.028	0.979	927
	0.2	0.917	343	0.353	0.029	0.366	0.136	0.1492	1.000	304	0.308	0.082	0.985	0.943	948
	0.3	0.888	376	0.373	0.042	0.389	0.145	0.2122	1.001	320	0.308	0.091	0.949	0.913	970
	0.4	0.864	415	0.391	0.053	0.409	0.161	0.2701	1.002	342	0.308	0.100	0.920	0.888	991
	0.5	0.843	459	0.407	0.064	0.427	0.180	0.3239	1.003	369	0.308	0.108	0.894	0.866	1013
	0.6	0.825	507	0.423	0.074	0.444	0.200	0.3744	1.005	398	0.309	0.117	0.872	0.847	1034
	0.7	0.810	559	0.437	0.083	0.459	0.221	0.4221	1.006	431	0.309	0.125	0.852	0.830	1056
	0.8	0.796	613	0.451	0.092	0.473	0.244	0.4675	1.007	465	0.310	0.134	0.834	0.815	1077
	0.9	0.783	669	0.465	0.101	0.487	0.268	0.5108	1.009	500	0.310	0.142	0.817	0.801	1099
	1.0	0.772	727	0.477	0.109	0.500	0.292	0.5524	1.010	536	0.311	0.150	0.802	0.788	1120
	1.1	0.762	786	0.490	0.117	0.512	0.318	0.5924	1.012	573	0.311	0.158	0.788	0.776	1142
	1.2	0.752	846	0.502	0.124	0.523	0.345	0.6309	1.014	610	0.312	0.166	0.775	0.765	1163
	1.3	0.743	907	0.513	0.132	0.534	0.372	0.6682	1.015	647	0.312	0.174	0.763	0.754	1185

	0.1	0.933	310	0.352	0.029	0.366	0.136	0.1492	1.000	304	0.308	0.082	0.965	970
	0.2	0.917	343	0.353	0.029	0.366	0.136	0.1492	1.000	304	0.308	0.091	0.949	0.913	970
	0.3	0.888	376	0.373	0.042	0.389	0.145	0.2122	1.001	320	0.308	0.100	0.920	0.888	991
	0.4	0.864	415	0.391	0.053	0.409	0.161	0.2701	1.002	342	0.308	0.100	0.894	0.866	1013
	0.5	0.843	459	0.407	0.064	0.427	0.180	0.3239	1.003	369	0.308	0.108	0.872	0.847	1034
	0.6	0.825	507	0.423	0.074	0.444	0.200	0.3744	1.005	398	0.309	0.117	0.852	0.830	1056
	0.7	0.810	559	0.437	0.083	0.459	0.221	0.4221	1.006	431	0.309	0.125	0.834	0.815	1077
	0.8	0.796	613	0.451	0.092	0.473	0.244	0.4675	1.007	465	0.310	0.134	0.817	0.801	1099
	0.9	0.783	669	0.465	0.101	0.487	0.268	0.5108	1.009	500	0.310	0.142	0.802	0.788	1120
	1.0	0.772	727	0.477	0.109	0.500	0.292	0.5524	1.010	536	0.311	0.150	0.788	0.776	1142
	1.1	0.762	786	0.490	0.117	0.512	0.318	0.5924	1.012	573	0.311	0.158	0.775	0.765	1163
	1.2	0.752	846	0.502	0.124	0.523	0.345	0.6309	1.014	610	0.312	0.166	0.763	0.754	1185
	1.3	0.743	907	0.513	0.132	0.534	0.372	0.6682	1.015	647	0.312	0.174	0.752	0.745	1206
	1.4	0.735	968	0.524	0.139	0.544	0.400	0.7044	1.017	685	0.313	0.182	0.741	0.735	1228
	1.5	0.727	1029	0.535	0.146	0.555	0.429	0.7394	1.018	722	0.313	0.190	0.731	0.727	1249
	1.6	0.720	1090	0.545	0.152	0.564	0.460	0.7736	1.020	759	0.314	0.198	0.722	0.719	1271
	1.7	0.714	1152	0.556	0.159	0.574	0.491	0.8068	1.022	796	0.314	0.206	0.713	0.711	1292
	1.8	0.708	1213	0.566	0.165	0.583	0.523	0.8392	1.023	833	0.315	0.214	0.704	0.703	1313
	1.9	0.702	1274	0.575	0.172	0.592	0.555	0.8709	1.025	869	0.315	0.221	0.696	0.696	1335
	2.0	0.696	1335	0.585	0.178	0.600	0.589	0.9018	1.026	905	0.316	0.229			
Cd	0.	1.000	293	0.244	0.	0.244	-0.	0.	1.000	293	0.244	0.076	1.166	1.039	721
	0.1	0.877	376	0.307	0.038	0.325	0.280	0.2577	1.002	312	0.245	0.121	0.953	0.915	770
	0.2	0.815	475	0.354	0.065	0.377	0.360	0.4477	1.006	362	0.246	0.161	0.867	0.848	818
	0.3	0.774	582	0.392	0.089	0.418	0.483	0.6055	1.012	423	0.247	0.199	0.814	0.802	867
	0.4	0.745	693	0.426	0.109	0.453	0.629	0.7435	1.017	486	0.249	0.236	0.775	0.766	916
	0.5	0.722	802	0.456	0.127	0.482	0.795	0.8676	1.023	548	0.250	0.272	0.743	0.738	965
	0.6	0.704	909	0.484	0.143	0.509	0.980	0.9813	1.029	608	0.251	0.308	0.717	0.714	1014
	0.7	0.688	1012	0.510	0.159	0.534	1.185	1.0869	1.034	665	0.253	0.344	0.694	0.693	1063
	0.8	0.675	1112	0.534	0.173	0.556	1.410	1.1859	1.039	721	0.254	0.379	0.675	0.675	1112
	0.9	0.664	1208	0.557	0.187	0.577	1.655	1.2795	1.044	774	0.255	0.414			
	1.0	0.654	1301	0.579	0.200	0.597	1.922	1.3683	1.049	824	0.256	0.449			
	1.1	0.646	1390	0.599	0.212	0.616	2.212	1.4531	1.053	872	0.257	0.484			
	1.2	0.638	1475	0.619	0.224	0.634	2.525	1.5344	1.058	919	0.258	0.518			
	1.3	0.631	1558	0.638	0.236	0.651	2.862	1.6125	1.062	963	0.259	0.553			
	1.4	0.624	1638	0.657	0.247	0.667	3.225	1.6879	1.066	1006	0.260	0.587			
Co	0.	1.000	293	0.475	0.	0.475	-0.	0.	1.000	293	0.475	0.149	1.042	1.017	746
	0.1	0.955	311	0.505	0.022	0.511	0.351	0.0629	1.000	294	0.475	0.169	0.996	0.972	764
	0.2	0.920	333	0.532	0.043	0.541	0.290	0.1195	1.000	301	0.475	0.187	0.950	0.936	783
	0.3	0.890	360	0.556	0.061	0.567	0.305	0.1713	1.001	314	0.475	0.205	0.914	0.906	801
	0.4	0.865	393	0.579	0.078	0.591	0.332	0.2194	1.001	333	0.476	0.223	0.885	0.880	820
	0.5	0.843	431	0.600	0.094	0.612	0.364	0.2645	1.002	356	0.476	0.239	0.862	0.857	838
	0.6	0.823	474	0.621	0.110	0.631	0.399	0.3071	1.003	383	0.476	0.256	0.841	0.837	856
	0.7	0.806	520	0.640	0.124	0.649	0.436	0.3475	1.004	414	0.477	0.273	0.822	0.819	875
	0.8	0.791	570	0.658	0.138	0.665	0.475	0.3861	1.006	446	0.477	0.289	0.804	0.802	893
	0.9	0.776	623	0.676	0.151	0.681	0.516	0.4230	1.007	480	0.478	0.305	0.789	0.786	911
	1.0	0.764	679	0.693	0.164	0.695	0.558	0.4586	1.008	516	0.479	0.321	0.774	0.772	930
	1.1	0.752	736	0.709	0.176	0.709	0.602	0.4929	1.010	553	0.479	0.336	0.760	0.759	948
	1.2	0.741	794	0.725	0.188	0.722	0.647	0.5260	1.011	591	0.480	0.352	0.748	0.747	966
	1.3	0.731	855	0.740	0.199	0.734	0.693	0.5581	1.012	629	0.481	0.367	0.736	0.735	985
	1.4	0.721	916	0.755	0.210	0.746	0.741	0.5892	1.014	668	0.481	0.383	0.724	0.724	1003
	1.5	0.712	977	0.769	0.221	0.757	0.790	0.6195	1.015	707	0.482	0.398	0.714	0.714	1022
	1.6	0.704	1040	0.783	0.232	0.768	0.841	0.6490	1.017	746	0.483	0.413	0.704	0.704	1040
Cr	0.	1.000	293	0.522	0.	0.522	-0.	0.	1.000	293	0.522	0.083	1.041	1.017	1181
	0.1	0.955	316	0.559	0.025	0.569	0.134	0.0708	1.000	296	0.522	0.095	0.981	0.971	1213
	0.2	0.919	350	0.591	0.048	0.608	0.141	0.1337	1.000	313	0.522	0.106	0.942	0.936	1245
	0.3	0.891	399	0.621	0.068	0.642	0.158	0.1910	1.001	344	0.522	0.117	0.910	0.906	1277
	0.4	0.866	463	0.649	0.087	0.672	0.178	0.2438	1.002	387	0.523	0.128	0.882	0.881	1308
	0.5	0.845	539	0.675	0.104	0.700	0.200	0.2931	1.003	439	0.523	0.138	0.859	0.859	1340
	0.6	0.827	626	0.699	0.121	0.724	0.223	0.3396	1.004	499	0.524	0.149	0.839	0.840	1372
									1.005	565	0.524	0.159	0.821	0.822	1404

(2)

	0.5	0.843	431	0.600	0.094	0.612	0.364	0.2645	1.002	330	0.476	0.256	0.841	0.837	856
	0.6	0.823	474	0.621	0.110	0.631	0.399	0.3071	1.003	383	0.476	0.256	0.841	0.837	856
	0.7	0.806	520	0.640	0.124	0.649	0.436	0.3475	1.004	414	0.477	0.273	0.822	0.819	875
	0.8	0.791	570	0.658	0.138	0.665	0.475	0.3861	1.006	446	0.477	0.289	0.804	0.802	893
	0.9	0.776	623	0.676	0.151	0.681	0.516	0.4230	1.007	480	0.478	0.305	0.789	0.786	911
	1.0	0.764	679	0.693	0.164	0.695	0.558	0.4586	1.008	516	0.479	0.321	0.774	0.772	930
	1.1	0.752	736	0.709	0.176	0.709	0.602	0.4929	1.010	553	0.479	0.336	0.760	0.759	948
	1.2	0.741	794	0.725	0.188	0.722	0.647	0.5260	1.011	591	0.480	0.352	0.748	0.747	966
	1.3	0.731	855	0.740	0.199	0.734	0.693	0.5581	1.012	629	0.481	0.367	0.736	0.735	985
	1.4	0.721	916	0.755	0.210	0.746	0.741	0.5892	1.014	668	0.481	0.383	0.724	0.724	1003
	1.5	0.712	977	0.769	0.221	0.757	0.790	0.6195	1.015	707	0.482	0.398	0.714	0.714	1022
	1.6	0.704	1040	0.783	0.232	0.768	0.841	0.6490	1.017	746	0.483	0.413	0.704	0.704	1040
Cr	0.	1.000	293	0.522	0.	0.522	-0.	0.	1.000	293	0.522	0.083	1.041	1.017	1181
	0.1	0.955	316	0.559	0.025	0.569	0.134	0.0708	1.000	296	0.522	0.095	0.981	0.971	1213
	0.2	0.919	350	0.591	0.048	0.608	0.141	0.1337	1.000	313	0.522	0.106	0.942	0.936	1245
	0.3	0.891	399	0.621	0.068	0.642	0.158	0.1910	1.001	344	0.522	0.117	0.910	0.906	1277
	0.4	0.866	463	0.649	0.087	0.672	0.178	0.2438	1.002	387	0.523	0.128	0.882	0.881	1308
	0.5	0.845	539	0.675	0.104	0.700	0.200	0.2931	1.003	439	0.523	0.138	0.859	0.859	1340
	0.6	0.827	626	0.699	0.121	0.724	0.223	0.3396	1.004	499	0.524	0.149	0.839	0.840	1372
	0.7	0.811	722	0.722	0.137	0.747	0.247	0.3836	1.005	565	0.524	0.159	0.821	0.822	1404
	0.8	0.796	825	0.744	0.152	0.769	0.272	0.4255	1.006	635	0.525	0.169	0.804	0.807	1436
	0.9	0.783	934	0.765	0.166	0.789	0.299	0.4656	1.008	709	0.526	0.179	0.790	0.792	1468
	1.0	0.771	1047	0.785	0.179	0.808	0.325	0.5041	1.009	784	0.526	0.188	0.777	0.779	1499
	1.1	0.760	1165	0.804	0.193	0.826	0.353	0.5411	1.011	862	0.527	0.198	0.765	0.766	1531
	1.2	0.750	1285	0.823	0.205	0.843	0.382	0.5769	1.012	941	0.528	0.208	0.754	0.755	1563
	1.3	0.741	1408	0.841	0.218	0.859	0.411	0.6116	1.014	1021	0.529	0.217	0.743	0.744	1595
	1.4	0.732	1533	0.858	0.230	0.875	0.442	0.6451	1.015	1101	0.530	0.227	0.734	0.734	1627
	1.5	0.724	1658	0.875	0.241	0.890	0.473	0.6778	1.017	1181	0.530	0.236	0.725	0.724	1658
Cu	0.	1.000	293	0.396	0.	0.396	-0.	0.	1.000	293	0.396	0.124	1.079	1.026	802
	0.1	0.940	322	0.435	0.026	0.445	0.323	0.0978	1.000	296	0.396	0.149	0.999	0.966	827
	0.2	0.897	357	0.468	0.048	0.484	0.291	0.1817	1.001	309	0.396	0.173	0.943	0.922	852
	0.3	0.864	399	0.497	0.068	0.517	0.324	0.2564	1.002	332	0.397	0.196	0.902	0.887	877
	0.4	0.836	449	0.524	0.086	0.546	0.370	0.3243	1.003	361	0.397	0.218	0.870	0.859	902
	0.5	0.814	505	0.549	0.102	0.571	0.421	0.3870	1.005	395	0.398	0.239	0.843	0.834	926
	0.6	0.794	565	0.572	0.118	0.594	0.476	0.4456	1.007	432	0.399	0.260	0.820	0.813	951
	0.7	0.777	628	0.594	0.132	0.616	0.535	0.5008	1.009	471	0.399	0.281	0.799	0.794	976
	0.8	0.762	694	0.615	0.146	0.635	0.597	0.5531	1.011	511	0.400	0.302	0.781	0.777	1001
	0.9	0.749	761	0.634	0.159	0.654	0.663	0.6029	1.013	553	0.401	0.322	0.764	0.761	1026
	1.0	0.737	829	0.653	0.172	0.671	0.731	0.6505	1.015	595	0.402	0.342	0.749	0.747	1051
	1.1	0.726	898	0.671	0.184	0.687	0.802	0.6963	1.017	636	0.403	0.362	0.736	0.734	1075
	1.2	0.716	967	0.689	0.196	0.703	0.876	0.7403	1.019	678	0.403	0.382	0.723	0.722	1100
	1.3	0.707	1036	0.706	0.207	0.718	0.953	0.7829	1.021	720	0.404	0.402	0.711	0.711	1125
	1.4	0.698	1106	0.722	0.218	0.732	1.033	0.8241	1.023	761	0.405	0.421	0.700	0.700	1150
	1.5	0.690	1175	0.738	0.228	0.745	1.116	0.8640	1.026	802	0.406	0.441	0.690	0.690	1175
Mo	0.	1.000	293	0.516	0.	0.516	-0.	0.	1.000	293	0.516	0.077	1.028	1.011	1040
	0.1	0.966	306	0.538	0.018	0.542	0.118	0.0437	1.000	294	0.516	0.084	0.988	0.977	1061
	0.2	0.937	324	0.559	0.035	0.565	0.115	0.0842	1.000	301	0.516	0.091	0.955	0.948	1082
	0.3	0.912	350	0.579	0.051	0.585	0.122	0.1220	1.000	316	0.516	0.097	0.928	0.923	1102
	0.4	0.890	385	0.597	0.066	0.604	0.132	0.1577	1.001	338	0.516	0.103	0.904	0.901	1123
	0.5	0.870	427	0.614	0.080	0.621	0.143	0.1915	1.001	368	0.516	0.109	0.883	0.880	1144
	0.6	0.852	478	0.631	0.093	0.636	0.154	0.2238	1.002	404	0.517	0.115	0.864	0.862	1165
	0.7	0.836	537	0.647	0.106	0.651	0.166	0.2546	1.002	446	0.517	0.121	0.847	0.845	1185
	0.8	0.821	602	0.662	0.118	0.664	0.178	0.2843	1.003	493	0.517	0.127	0.831	0.829	1206
	0.9	0.808	673	0.677	0.130	0.677	0.191	0.3129	1.004	544	0.518	0.133	0.816	0.815	1227
	1.0	0.795	750	0.691	0.142	0.689	0.204	0.3405	1.005	598	0.518	0.139	0.802	0.802	1248
	1.1	0.783	831	0.705	0.153	0.700	0.218	0.3672	1.005	655	0.519	0.145	0.789	0.789	1268
	1.2	0.772	917	0.718	0.164	0.711	0.231	0.3931	1.006	715	0.519	0.150	0.777	0.777	1289
	1.3	0.762	1006	0.731	0.174	0.722	0.245	0.4183	1.007	777	0.519	0.156	0.766	0.766	1310
	1.4	0.752	1099	0.744	0.184	0.731	0.260	0.4428	1.008	841	0.520	0.162	0.755	0.755	1331
														0.745	1351

(3)

	1.4	0.732	1533	0.858	0.230	0.875	0.442	0.6451	1.017	1181	0.530	0.236	0.725	0.724	1030
	1.5	0.724	1658	0.875	0.241	0.890	0.473	0.6778							
Cu	0.	1.000	293	0.396	0.	0.396	-0.	0.	1.000	293	0.396	0.124	1.079	1.026	802
	0.1	0.940	322	0.435	0.026	0.445	0.323	0.0978	1.000	296	0.396	0.149	0.999	0.966	827
	0.2	0.897	357	0.468	0.048	0.484	0.291	0.1817	1.001	309	0.396	0.173	0.943	0.922	852
	0.3	0.864	399	0.497	0.068	0.517	0.324	0.2564	1.002	332	0.397	0.196	0.902	0.887	877
	0.4	0.836	449	0.524	0.086	0.546	0.370	0.3243	1.003	361	0.397	0.218	0.870	0.859	902
	0.5	0.814	505	0.549	0.102	0.571	0.421	0.3870	1.005	395	0.398	0.239	0.843	0.834	926
	0.6	0.794	565	0.572	0.118	0.594	0.476	0.4456	1.007	432	0.399	0.260	0.820	0.813	951
	0.7	0.777	628	0.594	0.132	0.616	0.535	0.5008	1.009	471	0.399	0.281	0.799	0.794	976
	0.8	0.762	694	0.615	0.146	0.635	0.597	0.5531	1.011	511	0.400	0.302	0.781	0.777	1001
	0.9	0.749	761	0.634	0.159	0.654	0.663	0.6029	1.013	553	0.401	0.322	0.764	0.761	1026
	1.0	0.737	829	0.653	0.172	0.671	0.731	0.6505	1.015	595	0.402	0.342	0.749	0.747	1051
	1.1	0.726	898	0.671	0.184	0.687	0.802	0.6963	1.017	636	0.403	0.362	0.736	0.734	1075
	1.2	0.716	967	0.689	0.196	0.703	0.876	0.7403	1.019	678	0.403	0.382	0.723	0.722	1100
	1.3	0.707	1036	0.706	0.207	0.718	0.953	0.7829	1.021	720	0.404	0.402	0.711	0.711	1125
	1.4	0.698	1106	0.722	0.218	0.732	1.033	0.8241	1.023	761	0.405	0.421	0.700	0.700	1150
	1.5	0.690	1175	0.738	0.228	0.745	1.116	0.8640	1.026	802	0.406	0.441	0.690	0.690	1175
Mo	0.	1.000	293	0.516	0.	0.516	-0.	0.	1.000	293	0.516	0.077	1.028	1.011	1040
	0.1	0.966	306	0.538	0.018	0.542	0.118	0.0437	1.000	294	0.516	0.084	0.988	0.977	1061
	0.2	0.937	324	0.559	0.035	0.565	0.115	0.0842	1.000	301	0.516	0.091	0.955	0.948	1082
	0.3	0.912	350	0.579	0.051	0.585	0.122	0.1220	1.000	316	0.516	0.097	0.928	0.923	1102
	0.4	0.890	385	0.597	0.066	0.604	0.132	0.1577	1.001	338	0.516	0.103	0.904	0.901	1123
	0.5	0.870	427	0.614	0.080	0.621	0.143	0.1915	1.001	368	0.516	0.109	0.883	0.880	1144
	0.6	0.852	478	0.631	0.093	0.636	0.154	0.2238	1.002	404	0.517	0.115	0.864	0.862	1165
	0.7	0.836	537	0.647	0.106	0.651	0.166	0.2546	1.002	446	0.517	0.121	0.847	0.845	1185
	0.8	0.821	602	0.662	0.118	0.664	0.178	0.2843	1.003	493	0.517	0.127	0.831	0.829	1206
	0.9	0.808	673	0.677	0.130	0.677	0.191	0.3129	1.004	544	0.518	0.133	0.816	0.815	1227
	1.0	0.795	750	0.691	0.142	0.689	0.204	0.3405	1.005	598	0.518	0.139	0.802	0.802	1248
	1.1	0.783	831	0.705	0.153	0.700	0.218	0.3672	1.005	655	0.519	0.145	0.789	0.789	1268
	1.2	0.772	917	0.718	0.164	0.711	0.231	0.3931	1.006	715	0.519	0.150	0.777	0.777	1289
	1.3	0.762	1006	0.731	0.174	0.722	0.245	0.4183	1.007	777	0.519	0.156	0.766	0.766	1310
	1.4	0.752	1099	0.744	0.184	0.731	0.260	0.4428	1.008	841	0.520	0.162	0.755	0.755	1331
	1.5	0.743	1194	0.756	0.194	0.741	0.274	0.4667	1.009	906	0.520	0.167	0.745	0.745	1351
	1.6	0.734	1293	0.768	0.204	0.750	0.289	0.4901	1.010	973	0.521	0.173	0.735	0.735	1372
	1.7	0.726	1393	0.780	0.214	0.759	0.305	0.5128	1.011	1040	0.522	0.178	0.726	0.726	1393
Ni	0.	1.000	293	0.465	0.	0.465	-0.	0.	1.000	293	0.465	0.139	1.045	1.018	759
	0.1	0.954	314	0.497	0.023	0.506	0.344	0.0706	1.000	294	0.465	0.160	0.992	0.973	779
	0.2	0.919	338	0.527	0.043	0.541	0.286	0.1333	1.000	302	0.465	0.179	0.950	0.937	798
	0.3	0.889	368	0.553	0.061	0.571	0.303	0.1904	1.001	317	0.465	0.197	0.917	0.907	818
	0.4	0.865	404	0.578	0.078	0.597	0.333	0.2431	1.002	338	0.465	0.215	0.890	0.881	838
	0.5	0.843	445	0.600	0.094	0.621	0.368	0.2923	1.003	363	0.466	0.233	0.866	0.859	857
	0.6	0.825	491	0.622	0.109	0.643	0.407	0.3387	1.004	392	0.466	0.250	0.846	0.839	877
	0.7	0.809	541	0.642	0.123	0.663	0.447	0.3826	1.005	424	0.467	0.267	0.826	0.822	897
	0.8	0.794	594	0.662	0.136	0.682	0.490	0.4244	1.006	457	0.468	0.284	0.809	0.806	916
	0.9	0.781	649	0.680	0.149	0.699	0.535	0.4644	1.008	493	0.468	0.301	0.794	0.791	936
	1.0	0.768	706	0.698	0.162	0.716	0.581	0.5028	1.009	529	0.469	0.317	0.779	0.778	956
	1.1	0.757	765	0.715	0.174	0.732	0.630	0.5398	1.011	566	0.470	0.334	0.766	0.765	975
	1.2	0.747	825	0.732	0.185	0.747	0.679	0.5755	1.012	604	0.470	0.350	0.754	0.753	995
	1.3	0.738	887	0.748	0.196	0.761	0.731	0.6101	1.014	643	0.471	0.366	0.743	0.742	1015
	1.4	0.729	948	0.764	0.207	0.775	0.784	0.6436	1.015	681	0.472	0.382	0.732	0.732	1034
	1.5	0.721	1011	0.779	0.217	0.788	0.838	0.6762	1.017	720	0.472	0.398	0.722	0.722	1054
	1.6	0.713	1074	0.793	0.228	0.800	0.894	0.7079	1.018	759	0.473	0.413	0.713	0.713	1074

TABLE II. Summary of calculations and results.

Material	Shock wave parameters								Isentropic release-wave parameters at P 0				Isentrope parameters		
	P	V_H/V_o	T_H	c_H	u_H	U	$c_{p,H}$	z	V/V_o	T	c	c_p	$V(G)/V_o$	V/V_o	T
Pb	0.	1.000	293	0.203	0.	0.203	-0.	0.	1.000	293	0.203	0.055	1.226	1.059	964
	0.1	0.865	380	0.255	0.035	0.266	0.183	0.2585	1.002	315	0.203	0.087	1.020	0.921	1016
	0.2	0.796	490	0.294	0.060	0.306	0.246	0.4490	1.007	374	0.204	0.117	0.913	0.848	1068
	0.3	0.751	612	0.326	0.081	0.337	0.335	0.6072	1.013	444	0.205	0.144	0.842	0.797	1120
	0.4	0.718	738	0.354	0.100	0.363	0.439	0.7454	1.019	517	0.207	0.171	0.790	0.758	1172
	0.5	0.693	863	0.379	0.116	0.385	0.556	0.8698	1.026	589	0.208	0.198	0.749	0.727	1224
	0.6	0.673	985	0.402	0.132	0.405	0.687	0.9838	1.032	658	0.209	0.224	0.716	0.700	1276
	0.7	0.656	1103	0.424	0.146	0.423	0.832	1.0896	1.037	725	0.210	0.250	0.688	0.678	1328
	0.8	0.642	1218	0.444	0.159	0.440	0.991	1.1888	1.043	789	0.212	0.275	0.664	0.658	1380
	0.9	0.630	1328	0.463	0.171	0.455	1.165	1.2825	1.049	850	0.213	0.301	0.643	0.640	1432
	1.0	0.619	1434	0.481	0.183	0.470	1.354	1.3715	1.054	908	0.214	0.327	0.625	0.624	1484
	1.1	0.609	1536	0.498	0.195	0.483	1.558	1.4565	1.059	964	0.215	0.352	0.609	0.609	1536
	1.2	0.601	1635	0.515	0.206	0.496	1.780	1.5379	1.064	1018	0.216	0.378			
	1.3	0.593	1730	0.531	0.216	0.509	2.018	1.6162	1.068	1069	0.217	0.403			
	1.4	0.586	1821	0.546	0.226	0.521	2.275	1.6917	1.073	1118	0.218	0.428			
Sn	0.	1.000	293	0.264	0.	0.264	-0.	0.	1.000	293	0.264	0.068	1.191	1.050	1100
	0.1	0.871	380	0.326	0.042	0.338	0.182	0.2355	1.002	319	0.264	0.103	0.990	0.919	1161
	0.2	0.802	505	0.373	0.074	0.386	0.252	0.4120	1.006	391	0.266	0.136	0.874	0.846	1223
	0.3	0.757	653	0.412	0.100	0.423	0.342	0.5596	1.011	480	0.267	0.167	0.812	0.795	1285
	0.4	0.724	809	0.446	0.123	0.454	0.445	0.6890	1.017	575	0.269	0.196	0.768	0.756	1347
	0.5	0.698	968	0.477	0.144	0.481	0.560	0.8056	1.023	669	0.270	0.226	0.733	0.724	1408
	0.6	0.677	1125	0.505	0.163	0.505	0.687	0.9126	1.029	762	0.272	0.255	0.703	0.698	1470
	0.7	0.659	1280	0.531	0.181	0.526	0.826	1.0121	1.034	851	0.273	0.283	0.678	0.675	1532
	0.8	0.644	1430	0.556	0.198	0.546	0.978	1.1054	1.039	937	0.274	0.312	0.656	0.654	1593
	0.9	0.631	1576	0.579	0.213	0.565	1.143	1.1936	1.045	1020	0.276	0.340	0.638	0.636	1655
	1.0	0.620	1717	0.601	0.228	0.582	1.321	1.2774	1.050	1100	0.277	0.368	0.620	0.620	1717
	1.1	0.610	1854	0.622	0.243	0.598	1.512	1.3574	1.054	1176	0.278	0.397			
	1.2	0.601	1986	0.643	0.257	0.614	1.717	1.4341	1.059	1249	0.280	0.425			
	1.3	0.593	2114	0.662	0.270	0.628	1.937	1.5079	1.064	1320	0.281	0.453			
	1.4	0.585	2238	0.681	0.282	0.642	2.172	1.5791	1.068	1388	0.282	0.481			
Th	0.	1.000	293	0.213	0.	0.213	-0.	0.	1.000	293	0.213	0.028	1.242	1.070	2336
	0.1	0.869	385	0.256	0.033	0.260	0.059	0.2005	1.001	330	0.213	0.041	1.039	0.938	2428
	0.2	0.795	555	0.289	0.059	0.290	0.083	0.3552	1.005	439	0.214	0.052	0.914	0.860	2521
	0.3	0.744	775	0.317	0.081	0.313	0.111	0.4860	1.010	584	0.215	0.063	0.832	0.805	2614
	0.4	0.706	1022	0.341	0.100	0.332	0.142	0.6013	1.015	743	0.216	0.074	0.774	0.761	2706
	0.5	0.676	1281	0.364	0.118	0.348	0.177	0.7057	1.021	906	0.218	0.084	0.730	0.726	2799
	0.6	0.652	1544	0.384	0.134	0.362	0.215	0.8017	1.026	1068	0.219	0.094	0.694	0.696	2891
	0.7	0.631	1806	0.403	0.149	0.374	0.256	0.8911	1.032	1227	0.220	0.104	0.665	0.670	2984
	0.8	0.614	2065	0.421	0.163	0.386	0.300	0.9750	1.037	1382	0.221	0.114	0.640	0.647	3076
	0.9	0.598	2320	0.438	0.176	0.397	0.348	1.0545	1.042	1533	0.222	0.124	0.619	0.627	3169
	1.0	0.585	2569	0.454	0.189	0.407	0.399	1.1301	1.047	1678	0.223	0.134	0.601	0.608	3262
	1.1	0.573	2812	0.470	0.201	0.416	0.453	1.2023	1.052	1819	0.224	0.144	0.585	0.591	3354
	1.2	0.562	3049	0.484	0.212	0.425	0.511	1.2716	1.057	1955	0.225	0.154	0.570	0.575	3447
	1.3	0.552	3280	0.499	0.223	0.433	0.573	1.3383	1.062	2086	0.226	0.164	0.558	0.561	3539
	1.4	0.543	3505	0.512	0.234	0.441	0.638	1.4027	1.066	2213	0.227	0.174	0.546	0.548	3632
	1.5	0.535	3724	0.526	0.244	0.448	0.707	1.4649	1.070	2336	0.228	0.184	0.535	0.535	3724

	1.4	0.585	2238	0.681	0.282	0.642	2.172	1.5791	1.068	1388	0.282	0.481		
Th	0.	1.000	293	0.213	0.	0.213	-0.	0.	1.000	293	0.213	0.028	1.242	1.070	2336
	0.1	0.869	385	0.256	0.033	0.260	0.059	0.2005	1.001	330	0.213	0.041	1.039	0.938	2428
	0.2	0.795	555	0.289	0.059	0.290	0.083	0.3552	1.005	439	0.214	0.052	0.914	0.860	2521
	0.3	0.744	775	0.317	0.081	0.313	0.111	0.4860	1.010	584	0.215	0.063	0.832	0.805	2614
	0.4	0.706	1022	0.341	0.100	0.332	0.142	0.6013	1.015	743	0.216	0.074	0.774	0.761	2706
	0.5	0.676	1281	0.364	0.118	0.348	0.177	0.7057	1.021	906	0.218	0.084	0.730	0.726	2799
	0.6	0.652	1544	0.384	0.134	0.362	0.215	0.8017	1.026	1068	0.219	0.094	0.694	0.696	2891
	0.7	0.631	1806	0.403	0.149	0.374	0.256	0.8911	1.032	1227	0.220	0.104	0.665	0.670	2984
	0.8	0.614	2065	0.421	0.163	0.386	0.300	0.9750	1.037	1382	0.221	0.114	0.640	0.647	3076
	0.9	0.598	2320	0.438	0.176	0.397	0.348	1.0545	1.042	1533	0.222	0.124	0.619	0.627	3169
	1.0	0.585	2569	0.454	0.189	0.407	0.399	1.1301	1.047	1678	0.223	0.134	0.601	0.608	3262
	1.1	0.573	2812	0.470	0.201	0.416	0.453	1.2023	1.052	1819	0.224	0.144	0.585	0.591	3354
	1.2	0.562	3049	0.484	0.212	0.425	0.511	1.2716	1.057	1955	0.225	0.154	0.570	0.575	3447
	1.3	0.552	3280	0.499	0.223	0.433	0.573	1.3383	1.062	2086	0.226	0.164	0.558	0.561	3539
	1.4	0.543	3505	0.512	0.234	0.441	0.638	1.4027	1.066	2213	0.227	0.174	0.546	0.548	3632
	1.5	0.535	3724	0.526	0.244	0.448	0.707	1.4649	1.070	2336	0.228	0.184	0.535	0.535	3724
T1	0.	1.000	293	0.478	0.	0.478	-0.	0.	1.000	293	0.478	0.128	1.064	1.023	1189
	0.1	0.919	327	0.524	0.042	0.524	0.208	0.0964	1.000	301	0.478	0.154	0.956	0.942	1233
	0.2	0.860	386	0.564	0.079	0.559	0.239	0.1793	1.001	335	0.478	0.178	0.893	0.882	1277
	0.3	0.815	473	0.599	0.111	0.586	0.283	0.2531	1.003	394	0.479	0.201	0.843	0.835	1321
	0.4	0.777	584	0.631	0.141	0.609	0.331	0.3203	1.005	470	0.480	0.224	0.801	0.796	1365
	0.5	0.746	713	0.661	0.168	0.629	0.383	0.3824	1.007	558	0.481	0.246	0.765	0.762	1409
	0.6	0.719	855	0.688	0.193	0.646	0.438	0.4404	1.009	655	0.482	0.268	0.734	0.733	1453
	0.7	0.696	1007	0.714	0.217	0.662	0.496	0.4950	1.012	757	0.484	0.289	0.707	0.707	1497
	0.8	0.675	1167	0.739	0.240	0.676	0.556	0.5468	1.015	862	0.485	0.310	0.684	0.684	1541
	0.9	0.657	1333	0.763	0.262	0.688	0.620	0.5961	1.017	970	0.486	0.331	0.662	0.663	1586
	1.0	0.641	1502	0.785	0.282	0.700	0.686	0.6433	1.020	1079	0.488	0.352	0.643	0.643	1630
	1.1	0.626	1674	0.807	0.302	0.711	0.755	0.6887	1.023	1189	0.489	0.373	0.625	0.626	1674
T1	0.	1.000	293	0.186	0.	0.186	-0.	0.	1.000	293	0.186	0.062	1.241	1.055	763
	0.1	0.853	385	0.239	0.035	0.250	0.260	0.2876	1.003	315	0.186	0.103	0.979	0.905	813
	0.2	0.781	489	0.278	0.061	0.289	0.342	0.4952	1.009	367	0.187	0.140	0.859	0.828	862
	0.3	0.736	600	0.310	0.082	0.319	0.468	0.6665	1.016	428	0.189	0.175	0.795	0.776	911
	0.4	0.703	710	0.338	0.100	0.344	0.619	0.8157	1.023	490	0.190	0.209	0.750	0.736	961
	0.5	0.679	818	0.362	0.117	0.366	0.793	0.9496	1.030	550	0.191	0.243	0.713	0.704	1010
	0.6	0.658	922	0.385	0.132	0.385	0.989	1.0721	1.037	607	0.193	0.277	0.683	0.677	1060
	0.7	0.642	1021	0.406	0.146	0.402	1.208	1.1858	1.043	662	0.194	0.310	0.657	0.654	1109
	0.8	0.628	1117	0.426	0.159	0.418	1.452	1.2922	1.049	714	0.195	0.343	0.635	0.634	1158
	0.9	0.616	1208	0.445	0.171	0.433	1.721	1.3927	1.055	763	0.196	0.375	0.616	0.616	1208
	1.0	0.605	1295	0.463	0.183	0.447	2.017	1.4881	1.061	810	0.197	0.408			
	1.1	0.596	1378	0.479	0.194	0.461	2.340	1.5791	1.066	855	0.198	0.441			
	1.2	0.587	1458	0.496	0.204	0.473	2.694	1.6664	1.071	897	0.199	0.473			
	1.3	0.580	1535	0.511	0.215	0.485	3.080	1.7502	1.076	938	0.200	0.506			
	1.4	0.573	1609	0.526	0.225	0.497	3.499	1.8310	1.081	977	0.201	0.538			
	1.5	0.567	1680	0.541	0.234	0.508	3.954	1.9091	1.086	1014	0.202	0.571			
V	0.	1.000	293	0.511	0.	0.511	-0.	0.	1.000	293	0.511	0.121	1.035	1.017	995
	0.1	0.945	316	0.547	0.030	0.551	0.198	0.0710	1.000	296	0.511	0.138	0.972	0.962	1024
	0.2	0.902	349	0.579	0.057	0.584	0.207	0.1341	1.000	312	0.511	0.155	0.926	0.918	1053
	0.3	0.867	397	0.609	0.081	0.613	0.232	0.1914	1.001	342	0.511	0.171	0.889	0.883	1082
	0.4	0.838	459	0.636	0.103	0.637	0.262	0.2444	1.002	384	0.512	0.187	0.858	0.852	1111
	0.5	0.812	533	0.661	0.124	0.659	0.294	0.2938	1.003	435	0.513	0.202	0.829	0.826	1140
									1.005	493	0.513	0.218	0.804	0.802	1169

	0.2	0.860	586	0.304	0.019	0.337	0.283	0.2531	1.003	394	0.479	0.201	0.843	0.835	1321
	0.3	0.815	473	0.599	0.111	0.586	0.283	0.2531	1.003	394	0.479	0.201	0.843	0.835	1321
	0.4	0.777	584	0.631	0.141	0.609	0.331	0.3203	1.005	470	0.480	0.224	0.801	0.796	1365
	0.5	0.746	713	0.661	0.168	0.629	0.383	0.3824	1.007	558	0.481	0.246	0.765	0.762	1409
	0.6	0.719	855	0.688	0.193	0.646	0.438	0.4404	1.009	655	0.482	0.268	0.734	0.733	1453
	0.7	0.696	1007	0.714	0.217	0.662	0.496	0.4950	1.012	757	0.484	0.289	0.707	0.707	1497
	0.8	0.675	1167	0.739	0.240	0.676	0.556	0.5468	1.015	862	0.485	0.310	0.684	0.684	1541
	0.9	0.657	1333	0.763	0.262	0.688	0.620	0.5961	1.017	970	0.486	0.331	0.662	0.663	1586
	1.0	0.641	1502	0.785	0.282	0.700	0.686	0.6433	1.020	1079	0.488	0.352	0.643	0.643	1630
	1.1	0.626	1674	0.807	0.302	0.711	0.755	0.6887	1.023	1189	0.489	0.373	0.625	0.626	1674
T1	0.	1.000	293	0.186	0.	0.186	-0.	0.	1.000	293	0.186	0.062	1.241	1.055	763
	0.1	0.853	385	0.239	0.035	0.250	0.260	0.2876	1.003	315	0.186	0.103	0.979	0.905	813
	0.2	0.781	489	0.278	0.061	0.289	0.342	0.4952	1.009	367	0.187	0.140	0.859	0.828	862
	0.3	0.736	600	0.310	0.082	0.319	0.468	0.6665	1.016	428	0.189	0.175	0.795	0.776	911
	0.4	0.703	710	0.338	0.100	0.344	0.619	0.8157	1.023	490	0.190	0.209	0.750	0.736	961
	0.5	0.679	818	0.362	0.117	0.366	0.793	0.9496	1.030	550	0.191	0.243	0.713	0.704	1010
	0.6	0.658	922	0.385	0.132	0.385	0.989	1.0721	1.037	607	0.193	0.277	0.683	0.677	1060
	0.7	0.642	1021	0.406	0.146	0.402	1.208	1.1858	1.043	662	0.194	0.310	0.657	0.654	1109
	0.8	0.628	1117	0.426	0.159	0.418	1.452	1.2922	1.049	714	0.195	0.343	0.635	0.634	1158
	0.9	0.616	1208	0.445	0.171	0.433	1.721	1.3927	1.055	763	0.196	0.375	0.616	0.616	1208
	1.0	0.605	1295	0.463	0.183	0.447	2.017	1.4881	1.061	810	0.197	0.408			
	1.1	0.596	1378	0.479	0.194	0.461	2.340	1.5791	1.066	855	0.198	0.441			
	1.2	0.587	1458	0.496	0.204	0.473	2.694	1.6664	1.071	897	0.199	0.473			
	1.3	0.580	1535	0.511	0.215	0.485	3.080	1.7502	1.076	938	0.200	0.506			
	1.4	0.573	1609	0.526	0.225	0.497	3.499	1.8310	1.081	977	0.201	0.538			
	1.5	0.567	1680	0.541	0.234	0.508	3.954	1.9091	1.086	1014	0.202	0.571			
V	0.	1.000	293	0.511	0.	0.511	-0.	0.	1.000	293	0.511	0.121	1.035	1.017	995
	0.1	0.945	316	0.547	0.030	0.551	0.198	0.0710	1.000	296	0.511	0.138	0.972	0.962	1024
	0.2	0.902	349	0.579	0.057	0.584	0.207	0.1341	1.000	312	0.511	0.155	0.926	0.918	1053
	0.3	0.867	397	0.609	0.081	0.613	0.232	0.1914	1.001	342	0.511	0.171	0.889	0.883	1082
	0.4	0.838	459	0.636	0.103	0.637	0.262	0.2444	1.002	384	0.512	0.187	0.858	0.852	1111
	0.5	0.812	533	0.661	0.124	0.659	0.294	0.2938	1.003	435	0.513	0.202	0.829	0.826	1140
	0.6	0.790	618	0.685	0.144	0.678	0.328	0.3403	1.005	493	0.513	0.218	0.804	0.802	1169
	0.7	0.771	711	0.707	0.162	0.696	0.363	0.3844	1.006	556	0.514	0.232	0.782	0.781	1199
	0.8	0.753	810	0.729	0.180	0.713	0.400	0.4264	1.008	624	0.515	0.247	0.762	0.762	1228
	0.9	0.737	916	0.749	0.197	0.728	0.439	0.4666	1.009	694	0.516	0.262	0.744	0.744	1257
	1.0	0.723	1025	0.769	0.213	0.742	0.478	0.5051	1.011	768	0.517	0.276	0.728	0.728	1286
	1.1	0.709	1139	0.788	0.229	0.755	0.519	0.5422	1.013	842	0.517	0.290	0.713	0.713	1315
	1.2	0.697	1255	0.806	0.244	0.768	0.562	0.5781	1.015	918	0.518	0.305	0.699	0.699	1344
	1.3	0.686	1373	0.824	0.259	0.780	0.605	0.6128	1.017	995	0.519	0.319	0.686	0.686	1373
W	0.	1.000	293	0.400	0.	0.400	-0.	0.	1.000	293	0.400	0.053	1.027	1.013	1036
	0.1	0.970	305	0.416	0.013	0.419	0.090	0.0397	1.000	293	0.401	0.057	0.995	0.983	1054
	0.2	0.944	319	0.431	0.024	0.436	0.081	0.0766	1.000	298	0.401	0.061	0.966	0.957	1072
	0.3	0.921	339	0.445	0.035	0.451	0.084	0.1113	1.000	308	0.401	0.065	0.941	0.934	1089
	0.4	0.901	364	0.458	0.046	0.465	0.089	0.1442	1.001	323	0.401	0.069	0.919	0.913	1107
	0.5	0.882	395	0.471	0.055	0.477	0.095	0.1754	1.001	343	0.401	0.073	0.900	0.894	1124
	0.6	0.866	431	0.483	0.065	0.489	0.102	0.2053	1.001	368	0.401	0.076	0.882	0.877	1142
	0.7	0.850	473	0.494	0.074	0.500	0.109	0.2339	1.002	398	0.401	0.080	0.865	0.862	1160
	0.8	0.837	520	0.505	0.083	0.510	0.117	0.2615	1.002	431	0.401	0.084	0.850	0.847	1177
	0.9	0.824	571	0.516	0.091	0.520	0.124	0.2881	1.003	467	0.402	0.088	0.836	0.834	1195
	1.0	0.812	626	0.526	0.099	0.529	0.132	0.3139	1.004	505	0.402	0.091	0.823	0.821	1213
	1.1	0.800	685	0.536	0.107	0.538	0.140	0.3388	1.004	547	0.402	0.095	0.810	0.809	1230
	1.2	0.790	747	0.546	0.115	0.546	0.148	0.3630	1.005	590	0.403	0.098	0.799	0.798	1248
	1.3	0.780	812	0.555	0.122	0.554	0.157	0.3866	1.006	635	0.403	0.102	0.788	0.787	1266
	1.4	0.771	880	0.565	0.129	0.562	0.166	0.4096	1.007	682	0.403	0.105	0.778	0.777	1283
	1.5	0.762	950	0.574	0.136	0.569	0.174	0.4320	1.008	730	0.404	0.109	0.768	0.767	1301
	1.6	0.754	1022	0.583	0.143	0.576	0.183	0.4538	1.008	779	0.404	0.112	0.758	0.758	1319

(3)

	1.3	0.686	1373	0.824	0.259	0.780	0.605	0.6128	1.017	995	0.519	0.319	0.686	0.686	1373
W	0.	1.000	293	0.400	0.	0.400	-0.	0.	1.000	293	0.400	0.053	1.027	1.013	1036
	0.1	0.970	305	0.416	0.013	0.419	0.090	0.0397	1.000	293	0.401	0.057	0.995	0.983	1054
	0.2	0.944	319	0.431	0.024	0.436	0.081	0.0766	1.000	298	0.401	0.061	0.966	0.957	1072
	0.3	0.921	339	0.445	0.035	0.451	0.084	0.1113	1.000	308	0.401	0.065	0.941	0.934	1089
	0.4	0.901	364	0.458	0.046	0.465	0.089	0.1442	1.001	323	0.401	0.069	0.919	0.913	1107
	0.5	0.882	395	0.471	0.055	0.477	0.095	0.1754	1.001	343	0.401	0.073	0.900	0.894	1124
	0.6	0.866	431	0.483	0.065	0.489	0.102	0.2053	1.001	368	0.401	0.076	0.882	0.877	1142
	0.7	0.850	473	0.494	0.074	0.500	0.109	0.2339	1.002	398	0.401	0.080	0.865	0.862	1160
	0.8	0.837	520	0.505	0.083	0.510	0.117	0.2615	1.002	431	0.401	0.084	0.850	0.847	1177
	0.9	0.824	571	0.516	0.091	0.520	0.124	0.2881	1.003	467	0.402	0.088	0.836	0.834	1195
	1.0	0.812	626	0.526	0.099	0.529	0.132	0.3139	1.004	505	0.402	0.091	0.823	0.821	1213
	1.1	0.800	685	0.536	0.107	0.538	0.140	0.3388	1.004	547	0.402	0.095	0.810	0.809	1230
	1.2	0.790	747	0.546	0.115	0.546	0.148	0.3630	1.005	590	0.403	0.098	0.799	0.798	1248
	1.3	0.780	812	0.555	0.122	0.554	0.157	0.3866	1.006	635	0.403	0.102	0.788	0.787	1266
	1.4	0.771	880	0.565	0.129	0.562	0.166	0.4096	1.007	682	0.403	0.105	0.778	0.777	1283
	1.5	0.762	950	0.574	0.136	0.569	0.174	0.4320	1.008	730	0.404	0.109	0.768	0.767	1301
	1.6	0.754	1022	0.582	0.143	0.576	0.183	0.4538	1.008	779	0.404	0.112	0.758	0.758	1319
	1.7	0.746	1096	0.591	0.150	0.583	0.192	0.4752	1.009	829	0.404	0.116	0.750	0.750	1336
	1.8	0.738	1172	0.599	0.157	0.589	0.202	0.4961	1.010	880	0.405	0.119	0.741	0.741	1354
	1.9	0.731	1249	0.607	0.163	0.596	0.211	0.5166	1.011	931	0.405	0.122	0.733	0.733	1372
	2.0	0.725	1327	0.615	0.170	0.602	0.221	0.5367	1.012	984	0.405	0.126	0.725	0.725	1389
	2.1	0.718	1407	0.623	0.176	0.608	0.231	0.5564	1.013	1036	0.406	0.129	0.718	0.718	1407
Zn	0.	1.000	293	0.305	0.	0.305	-0.	0.	1.000	293	0.305	0.143	1.180	1.045	737
	0.1	0.895	352	0.365	0.038	0.380	0.576	0.1962	1.001	302	0.305	0.204	1.024	0.939	772
	0.2	0.834	416	0.411	0.068	0.432	0.586	0.3482	1.004	331	0.306	0.260	0.916	0.876	806
	0.3	0.793	488	0.450	0.093	0.472	0.723	0.4768	1.008	369	0.307	0.313	0.851	0.831	840
	0.4	0.762	564	0.485	0.115	0.507	0.893	0.5904	1.012	411	0.309	0.365	0.808	0.795	874
	0.5	0.737	641	0.516	0.136	0.537	1.086	0.6931	1.016	455	0.310	0.415	0.776	0.767	908
	0.6	0.717	718	0.545	0.154	0.564	1.299	0.7878	1.021	498	0.311	0.465	0.749	0.742	942
	0.7	0.701	794	0.572	0.171	0.588	1.533	0.8759	1.025	541	0.313	0.514	0.726	0.721	977
	0.8	0.686	868	0.597	0.188	0.610	1.786	0.9587	1.029	583	0.314	0.563	0.706	0.702	1011
	0.9	0.673	941	0.621	0.203	0.631	2.058	1.0370	1.034	623	0.315	0.611	0.687	0.685	1045
	1.0	0.662	1011	0.644	0.217	0.651	2.351	1.1116	1.038	662	0.316	0.660	0.671	0.670	1079
	1.1	0.652	1080	0.666	0.231	0.670	2.664	1.1828	1.042	701	0.318	0.708	0.657	0.656	1113
	1.2	0.643	1148	0.687	0.245	0.687	2.998	1.2512	1.045	737	0.319	0.755	0.643	0.643	1148
	1.3	0.635	1213	0.707	0.258	0.704	3.354	1.3170	1.049	773	0.320	0.803			
	1.4	0.628	1276	0.726	0.270	0.720	3.732	1.3804	1.053	808	0.321	0.851			
	1.5	0.621	1338	0.745	0.282	0.736	4.133	1.4419	1.056	841	0.322	0.898			

[a]These data were obtained from Dr. R. G. McQueen. They represent the numerical values from which the rightmost isentropes in Figs. 10 to 25 of Ref. 4 were plotted.

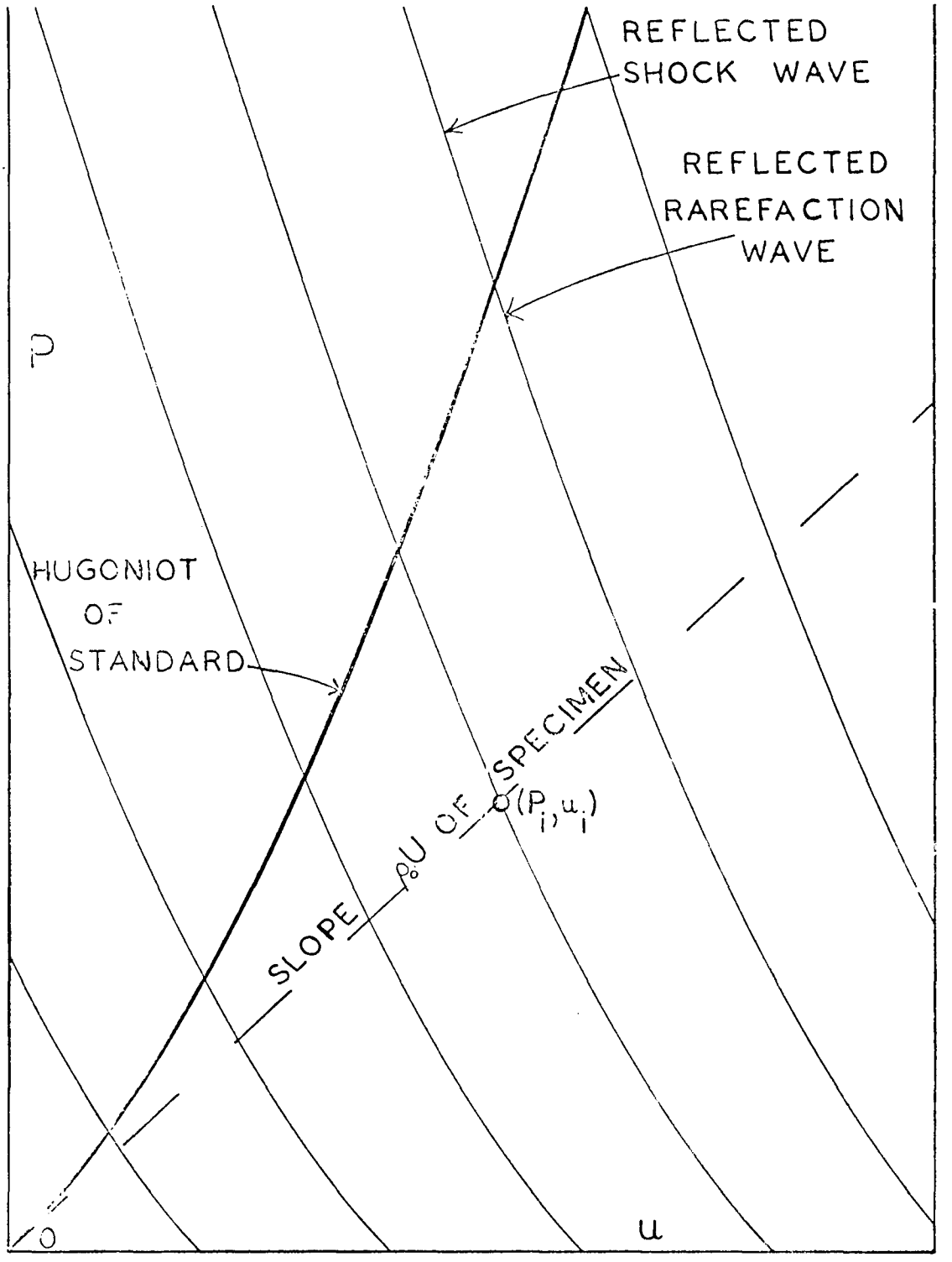
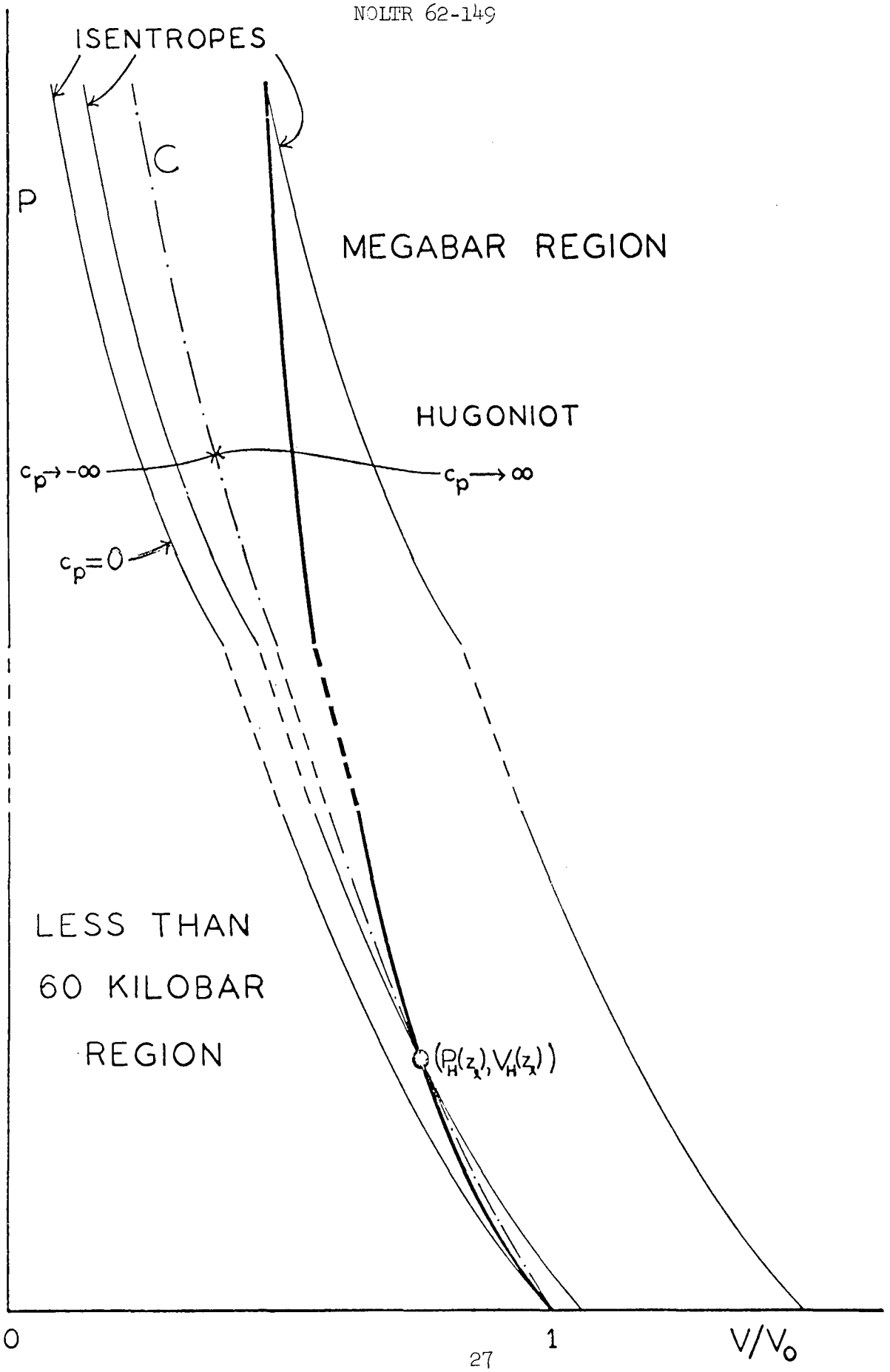


Fig. 1. Pressure versus particle velocity curves for an initial shock in a metal standard followed by a reflected shock or rarefaction wave, and a typical graphical solution to determine P_1, u_1 for a test specimen.

Fig. 2. Pressure versus volume curves for a metal that satisfies the mirror-image assumption. The dash-dot curve, C, is defined by Eq. (50) and is the locus of points on which $c_p \rightarrow \pm \infty$ depending upon the direction of approach. The intersection of C with Hugoniot occurs at $P_H(z_\ell)$, $V_H(z_\ell)$ where $P_H(z_\ell)$ lies between 10 to 50 kilobars for the 16 metals considered. The figure is split into a megabar region and a "less than 60 kilobar region".


ISENTROPES
C
P
MEGABAR REGION
HUGONIOT
$c_p \to -\infty$
$c_p \to \infty$
$c_p = 0$
LESS THAN
60 KILOBAR
REGION
$(P_H(z_1), V_H(z_1))$
0
1
V/V_o

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DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Metals (description)	METAD	Nickel	NICK	Compressible	COMR
Thermodynamic	THED	Lead	LEAD	Equation-of-state	EQUS
Mirror	MIRR	Tin	TINE	Anomalous	ANOM
Image	IMAG	Thorium	THOI	Behavior	PERF
Metals	META	Titanium	TITN	Comparison	CMRI
Silver	SILV	Thallium	THAL	Mie	MIEQ
Gold	GOLD	Vanadium	VANA	Grüneisen	GRUS
Cadmium	CADM	Tungsten	TUNG		
Cobalt	COBA	Zinc	ZINC		
Chromium	CHRM	Shock	SHOC		
Copper	COPP	Hugoniot	HUGO		
Molybdenum	MOLY	Curve	CURV		

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 62-149)
A COMPLETE E,P,V,T,S THERMODYNAMIC DESCRIPTION OF METALS BASED ON THE P,u MIRROR-IMAGE CONCEPT, by Julius W. Enig. 13 Aug. 1962. 27p. tables, graphs. Task FR-59 UNCLASSIFIED

Experimental relationship $U=c_0+au_H$ and $\alpha \equiv V^{-1}(\partial V/\partial T)_{P\approx 0}=$ constant gives thermodynamic description of metals in which metal appears less compressible than if described by Mie-Grüneisen equation of state. Anomalous behavior of c_p in low pressure neighborhood of initial state excludes simultaneous existance of Hugoniot satisfying U vs. u_H relationship and constant α in this region. Thermodynamic functions for 16 metals are calculated up to 2 megabars and compared with results obtained from Mie-Gruneisen equation.

1. Metals - Thermodynamic properties
2. Equations of state
3. Mie-Gruneisen equations
I. Title
II. Enig, Julius W.
III. Project

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